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Impact and Cost Evaluation of Electric Vehicle Integration on Medium Voltage Distribution Networks

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***Abstract*-- This paper presents the analysis of the impact of electric vehicle (EV) integration on medium voltage (MV) distribution networks and the cost evaluation of replacing the overloaded grid components. A number of EV charging scenarios have been studied. A 10 kV grid from the Bornholm Island in the city area has been used to carry out case studies. The case study results show that the secondary transformers are the bottleneck of the MV distribution networks and the increase of EV penetration leads to the overloading of secondary transformers. The cost of the transformer replacement has been evaluated. The transformer replacement cost reaches 72% of the total transformers value with 50% EV penetration and 3 Phase charging.**

***Index Terms*— Cost evaluation, EV, MV distribution network, transformer replacement**

I. Introduction

Electric vehicles (EVs) are considered as an increasingly important part of the solution when it comes to redirecting society towards a greener agenda dealing with the integration of wind power, solar cells, etc. in Danish and international context. The EVs has the advantage that they can be set to charge when there is a surplus of renewable energy in the grid, and can thus help reducing the consumption of limited fossil fuels, and lower CO2 emissions as Denmark has obliged to do according to international agreements [1]. In 2011 the wind power generation covered 28% of the demand (incl. grid losses). The Danish parliament has entered a new energy agreement and set a target of 50% penetration of wind power in 2020 and 100% penetration of renewable energy in 2035 for the electricity consumption [2]. This will lead to a huge change is the energy production system of Denmark [3].

The EVs can be also a part of the solution toward a greener environment and cutting greenhouse gas emissions, it can also cause major problems in regards to the existing power system equipment. Several studies have been made concerning the impact of EV integration on medium and low voltage grids and congestion issues [4] - [11]. Impact study of EV integration has been done to analyze the effects of different EV charging scenarios on power system components and voltage profiles, and identify the bottlenecks in the medium voltage (MV) distribution grids [5]. An analytical framework was developed to investigate the impacts of EV integration on distribution system thermal loading, voltage regulation, transformer loss of life, unbalances, losses, and harmonic distortion levels [6] - [7]. The impact of different EV charging scenarios on the transformer insulation life was studied using the Monte Carlo method based simulation [8].

The grid congestion caused by EV integration is depending on several parameters such as grid topology, EV penetration level, EV distribution within distribution grids and EV charging scenarios. The grid congestion from EVs is due to the fact that the load demand profile of consumers will change significantly from the prevailing load demand curves. Smart EV charging methods have developed to alleviate the congestion from EVs [9] - [11].

The work in this paper is to quantify the power system components that will be overloaded with different EV penetration levels and EV charging scenarios, and evaluate the cost of replacing the overloaded power system components.

The paper is arranged as follows. In Section II, the EV charging scenarios are briefly discussed. The method of EV impact on MV distribution networks and cost evaluation is described in Section III. In Section IV, an analysis of the transformer replacement cost is presented. In the end, conclusions are drawn.

II. EV Charging Scenarios

The EV charging management should ensure that the EV driving needs are met. The EV charging management can be done in different manners which can be divided into three categories: plug and charge, timed charging and EV fleet operator based charging. For the EV fleet operator based charging method, the EV fleet operator minimizes the charging cost taking into account energy prices. The plug and charge method can be divided into two sub-categories: plug and charge all day, and plug and charge home. The EV fleet operator based charging method can also be divided into two sub-categories: fleet all day and fleet night. The details of the five EV charging methods are listed in Table I.

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Table I

EV Charging Methods

Charging method	Description
Plugandcharge	EVs start charging when they are parked
Plugandchargehome	EVs start charging when they return home
Timed	EVs start charging at a certain time of the day (10pm)
Fleetallday	EV charging is scheduled during the low price time periods during the day by EV fleet operators when they are parked
Fleetnight	EV charging is scheduled during the low price time periods by EV aggregators when they are parked at home

The assumption of the plug_and_charge_all_day and the aggregator_all_day charging methods is that charging facility is available whenever the EVs are parked.

For the aggregator based charging method, it can be described as the optimization problem below.

Objective function

$$\min C^T E \tag{1}$$

subject to

$$0 \leq E_{n,t} u_{n,t} \leq E_{max} \; \forall \, t \tag{2}$$

$$SOC_{min} \leq SOC_{init} + \sum_{t=1}^{\tau} E_{n,t} u_t - \sum_{t=1}^{\tau+\tau_d} E_{n,d,t} v_t \leq SOC_{max} \; \forall \, t, n \tag{3}$$

$$u_{n,t} + v_{n,t} \leq 1 \tag{4}$$

$$v_t, u_t \in [0,1] \tag{5}$$

where C_t is electricity spot price at time t (DKK/kWh), $E_{n,t}$is charging Energy for EV n during period t (kWh), $E_{n,d,t}$ is driving Energy requirement for EV n during period t (kWh), E_{max} is Maximum charging energy during period t (kWh), SOC_{min} is Minimum battery state of charge, SOC_{init} is Initial battery state of charge (kWh), τ is set of time when vehicle is unavailable for charging, τ_d is set of durations for which vehicle is unavailable for charging, n is EV index, v_t and u_t are Binary control variables.

The objective function ensures the total cost of EV charging is minimized.

III. Method of EV Impact and Cost Analysis

In order to study the impact of EV integration on MV distribution system component loading and the replacement cost incurred, time series load flow analysis has been carried out with the conventional demand and the EV charging demand, and the MV distribution grid model. The EV impact and cost analysis is illustrated in Figure 1.

The steps of the EV impact and cost analysis method are listed below.

1. Calculate the EV demand according to the driving data, EV specification, charging option, EV penetration level and charging scenarios.
2. Calculate household demand using the demand types, typical demand profile and yearly electricity consumption.
3. Obtain the load profile at the 10/0.4 kV substations
4. Carry out time series power flow study with the 10 kV grid with the demand profile from Step 3 and the selected grid model
5. Determine the overloaded power components
6. Use the cost information of power system components to calculate the replacement cost

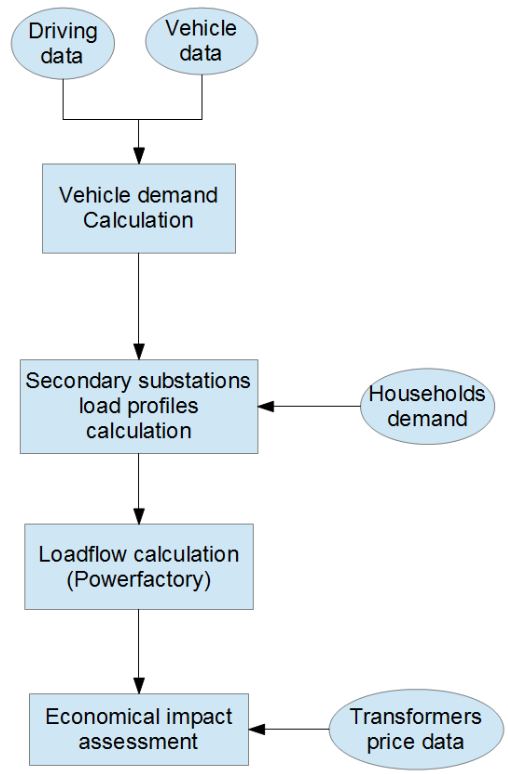

Figure 1 Outline of the data processing

For Step 2, Load profiles for each household are based on annual electricity consumption and are formed based on load profiles from the Danish Energy Association [4]. Those profiles are combined with the EV demand data from Step 1 to determine the demand at the 10/0.4 kV substations.

For Step 5, the overloading limit is set as 67% of the nominal capacity of power system components. The criteria are that 1/3 of the capacity is reserved for resupplying purposes, i.e. if a fault occurs at a feeder, two neighboring feeders will be used to resupply that feeder.

In order to calculate the cost of power system component replacement, the cost of power system components need to be obtained. In the paper, the transformers are the overloaded components at the MV distribution networks. Therefore, the cost information of transformers is obtained.

For calculating the cost of replacement, the transformer capacity is increased till the transformer is not overloaded.

The transformer cost information from [12], shown in Figure 2, is used to calculate the transformer replacement cost.

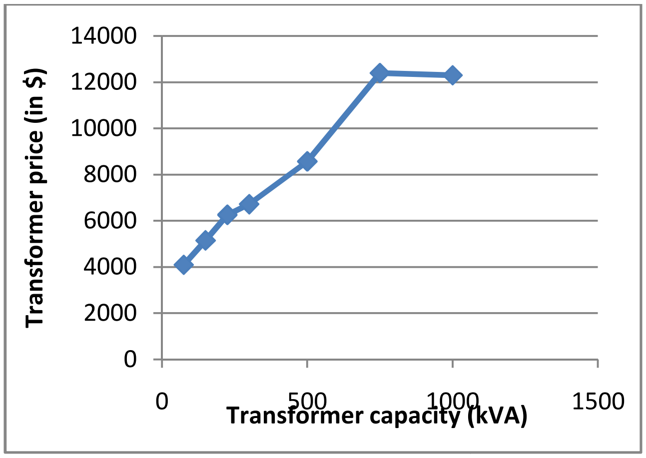

Figure 2 Distribution of transformer cost versus its capacity

According to [12], there is a linear relationship between the transformer cost and the transformer capacity if the transformer capacity is between 75 kVA and 750 kVA.

IV. EV Data and Grid Model

In order to obtain the number of the overloaded power system components under different EV penetration levels and different charging power, a number of case studies have been carried out. The details of the EV penetration levels, EV charging power, EV battery capacity and the grid model are described below.

A. *EV driving data*

The Driving data are from the Danish National Travel Survey [13]. The Danish driving data are highly detailed and provide significant insight into the driving habits of Danish residents. The relevant data used in this study are driving stop and start time, distance during driving periods, and day type. The EV availability for charging is defined as the periods during which the EV is parked. The EV availability on a working day is illustrated in Figure 3. Each horizontal section represents a single EV, with the white brown representing availability to charge, and the blue colour representing time periods when the EV is driving, and therefore is unavailable to charge.

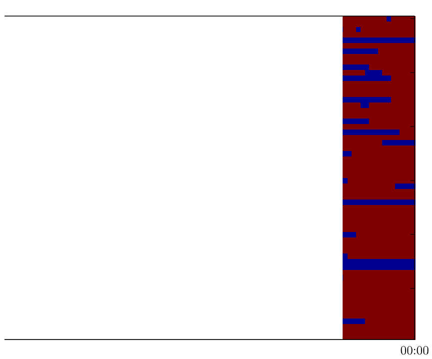

Figure 3 EV Availability on a Working Day

B. *EV penetration level and EV charging power*

For the case studies, a number of EV penetration levels have been considered which are 10%, 20%, 30%, 40% and 50%. The base case is without EVs.

For each EV penetration level, 1 Phase charging and 3 Phase charging with 16 A are considered. The charging power is 3.6kW and 11kW, respectively.

All the EVs are assumed to be same and have a standard battery capacity of 23.3kWh.

C. *Grid Model*

The 10kV MV grid in the northern part of Ronne on Bornholm has been used for the case studies. Ronne is the city area on Bornholm. It is expected that the loading will be higher in the city area. The 10kV MV grid in the northern part of Ronne is comprised of 30 10/0.4 substations, 65 connection lines and 31 10/0.4 kV transformers.

The 10 kV MV grid model of the northern part of Ronne is shown in Figure 4. In the Ronne Nord grid, the biggest distribution transformer is 630kVA and the total value of the transformer is 166.7 thousand $.

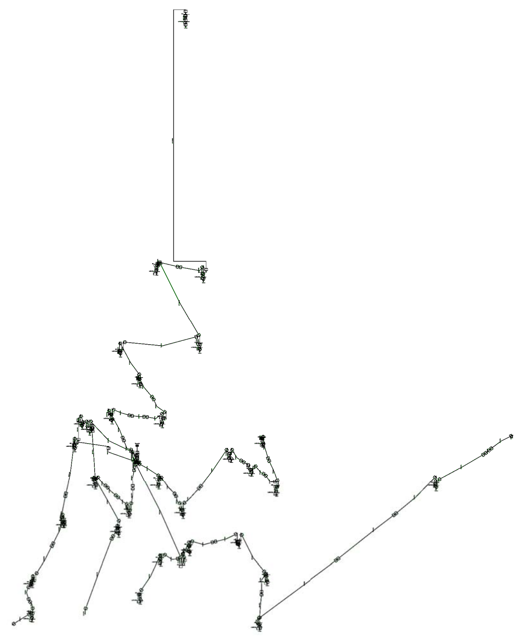

Figure 4Ronne Grid topology

V. Case Study Results

With the 5 EV penetration levels, 2 EV charging power, and 5 charging scenarios, 51 case studies have been carried out with the Ronne Nord grid model. The intention is to determine how many power system components are overloaded and the replacement cost incurred.

A. EV charging demand

The EV charging demands with 20% EV penetration for 1 Ph and 3 Ph charging are shown in Figure 5Figure 6. The EV fleet operator based on charging and timed charging cause high demand for specific hours. For the EV fleet operator based charging, the peak demand appears in the low price hour. For the timed charging, the peak demand appears in the hour when EVs start charging.

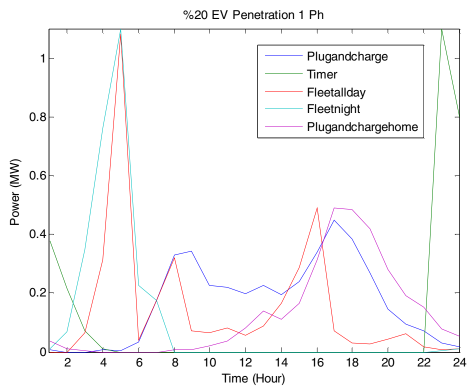

Figure 5 EV demand with 20% EV penetration for 1 Ph charging

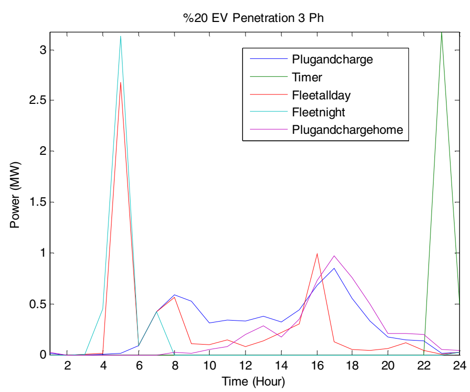

Figure 6 EV demand with 20% EV penetration for 3 Ph charging

B. *Results of the Overloading Study*

The overloading study is to determine what devices are the most impacted by the EV grid integration. The worst case scenario is used with 50% EV penetration and 3 Phase charging. The results of the overloading study with 50% EV penetration and 3 Phase charging are listed in Table II. It is shown that transformers are the most impacted devices.

Table II

Devices overloaded in the worst case scenario

Charging Scenario	Transformers overloaded	Lines overloaded	Voltage drops above 5%
plugandcharge	1	0	0
plugandcharge home	2	0	0
timer	15	1	0
fleetallday	3	0	0
fleetallnight	15	0	0

C. *Overloading of Transformers*

In the case of 1 Phase charging, the number of overloaded transformers with different EV penetration levels is shown in Figure 7.

For all the charging scenarios but one, the number of overloaded transformers is increased with the increase of the EV penetration level.

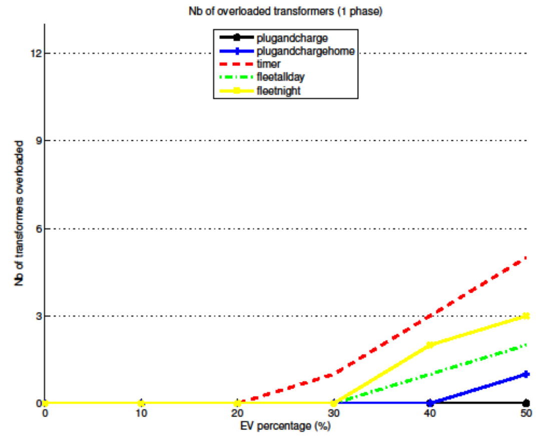

Figure 7 Number of overloaded transformers with different EV penetration levels and 1 Phase charging

The number of overloaded transformers with 3 Phase charging and different EV penetration levels is shown in Figure 8.

The number of transformers overloaded is increased with the increase of the EV penetration levels. The “timer” and “fleetnight” scenarios cause a high number of overloaded transformers (50% of the transformers for a 50% EV share) and the rest of the scenarios overload less than 10% of the transformers with 50% EV penetration.

From the results, the “timer” and “fleetnight” charging scenarios have the highest impact on the grid. Those two charging scenarios cause simultaneous charging and a big challenge to the grid operation.

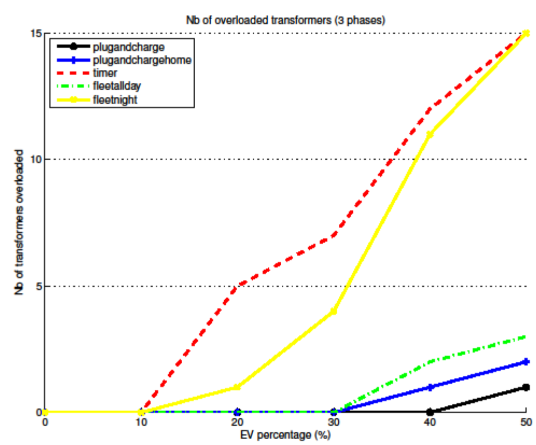

Figure 8 Number of overloaded transformers with different EV penetration levels and 3Pphases charging

D. *Replacement Cost Analysis*

The replacement cost of the overloaded transformers with the five EV penetration levels, and 1 and 3 Phase charging has been calculated and is shown in Figure 9 and Figure 10, respectively.

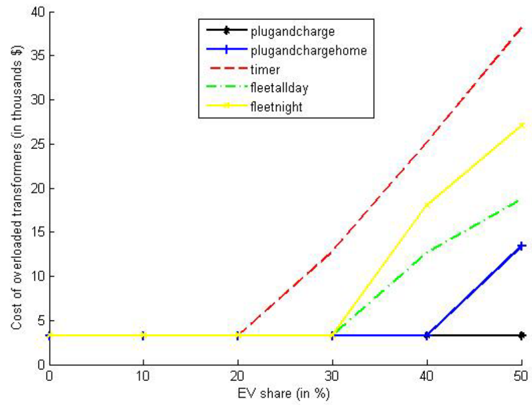

Figure 9 Cost of overloaded transformers replacement according to the EV share for one phase charging

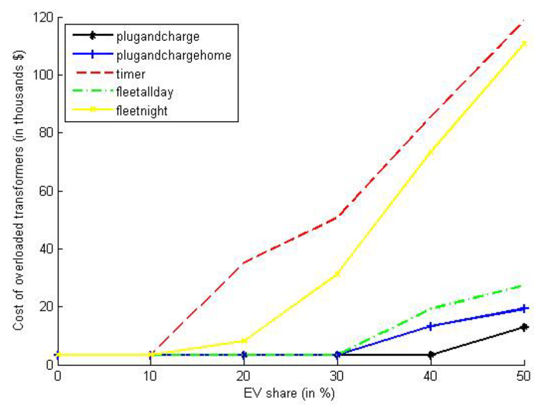

Figure 10 Replacement cost of overloaded transformers with different EV penetration levels and 3 Phase charging

For the one phase charging case, the replacement cost is always lower than the one for the 3 phase charging. Two main facts can be outlined:

- For the three scenarios "plugandcharge", "plugandchargehome" and "fleetallday", it can be seen that the replacement cost doesn't increase much between the one and three phase charging case. They stay under 25 thousand dollars.
- For the two scenarios "timer" and "fleetnight", the replacement cost highly increase between the one and three phase charging case. It increases by 300% for the 50% EV share. Furthermore, in the worst case scenario, 120 thousand dollars represents 72% of the total value of the secondary substation transformers of the Ronne Nord grid.

VI. Conclusions

The impact and cost evaluation of EV integration on MV grid has been carried out to quantify the effects of different EV penetration levels and charging options on the distribution grid upgrading cost. The study results show that the fleet based home charging with spot prices and the timed EV charging options may cause higher investment costs for the distribution grids.

The study gives a new glance on the impact of EV of the distribution grid. For the mid-term or long term planning, distribution system operators (DSOs) need to forecast their grid investments, therefore, this economic analysis gives important information for investment forecasting.

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